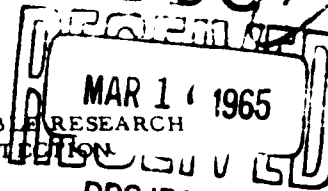


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THE ARCTIC SOLDIER: POSSIBLE RESEARCH  
SOLUTIONS FOR HIS PROTECTION

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Man is still fighting his two oldest enemies — his fellow men and his environment. When not required to battle both simultaneously, modern man has the latter reasonably under control. The cave has given way to the insulated home or the insulated quonset hut, the primitive campfire has developed through indoor fireplaces, the Chinese k'ang to modern central heating, and the bear skin robe has been supplanted by multilayered clothing systems incorporating natural and synthetic materials (21). So successful has man been in his terrestrial triumph over his environment that he now looks beyond wintering in a comfortable microclimate in the midst of the  $-100^{\circ}$  F Antarctic, toward conquering outer space. His success has been almost solely technological; modern man is probably less well adapted biologically for living in the cold than his cave dwelling ancestors, who were inured and acclimated to a degree of cold exposure which modern man has been clever enough to avoid. The technological secret to living comfortably at Thule, Point Barrow or Little America is to avoid the cold and stay in an auxiliary heated microclimate (6). Unfortunately, it is currently impossible to defend against an enemy and simultaneously remain in a heated shelter; for the foreseeable future, man, when giving battle to his enemies, will have to leave the auxiliary heated microclimate of his shelter and face the cold. He then must replace the shelter with a good clothing system, and depend on and conserve his own metabolic heat production for survival.

The current goal for cold weather clothing systems, as stated in the required military characteristics, is 8 hours tolerance while inactive at  $-40^{\circ}$  F when there is a 3 mph wind. This requirement has yet to be met. One of the most frustrating aspects of providing this level of protection is that it is easily done for all but 5 or 10% of the total body. The clothed active soldier in the Arctic has a surplus of body heat which is distributed to the hands and feet by way of the circulating blood. Unfortunately, the circulation to the hands and feet of the inactive soldier drops as he becomes cold, from about 100 cc/min to less than 1 cc/min, thus eliminating almost all circulatory heat input

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to the fingers and toes (8). Thus the hands and feet, representing only a very small part of the body, are the limiting factors in tolerance to the cold (14, 20) (Figure 1).

The well recognized geometrical relationships of small cylinders, i. e., that increasing insulation thickness results in an increased area for heat loss, prohibits adequate practical insulation for the fingers and toes at an ambient temperature of even  $-20^{\circ}\text{F}$ , using the best available insulating materials (19) (Figure 2).

Thus, conventional solutions are at an end of the line. The logical next step, one which somehow seems beyond the comprehension of many, is to turn again to technology to provide a tolerable microclimate. The history of auxiliary heating, studied since 1944, has recently been reviewed (18). Most of this early work involved extensive available power, as in airplanes; minimal power requirements were unknown but estimated as excessive on the basis of these earlier studies. The present paper summarizes results of a research program on auxiliary heating with minimum power, which has established the feasibility of two approaches: auxiliary heating for the extremities and, in the longer range, a conditioned air clothing system which has perhaps primary application in hot and/or toxic environments but could handle cold easily (17).

## METHODS

Subjects were chosen from volunteers in the military test group. All were young men of average stature, in good physical condition and without previous cold injury. The complete Army Quartermaster cold-dry standard clothing ensemble (35 lbs; 4.3 clo\*) was worn (Figure 3), except as noted below. The

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\*An arbitrary unit of thermal insulation, used in expressing the thermal insulation value of clothing. A suit of clothing has a thermal insulation value of one clo when it will maintain in comfort a resting-sitting human adult male whose metabolic rate is approximately 50 kilogram calories per square meter of body surface per hour, when the environmental temperature is  $70^{\circ}\text{F}$ . In terms of absolute thermal insulation units, one clo is  $0.18^{\circ}\text{C}$

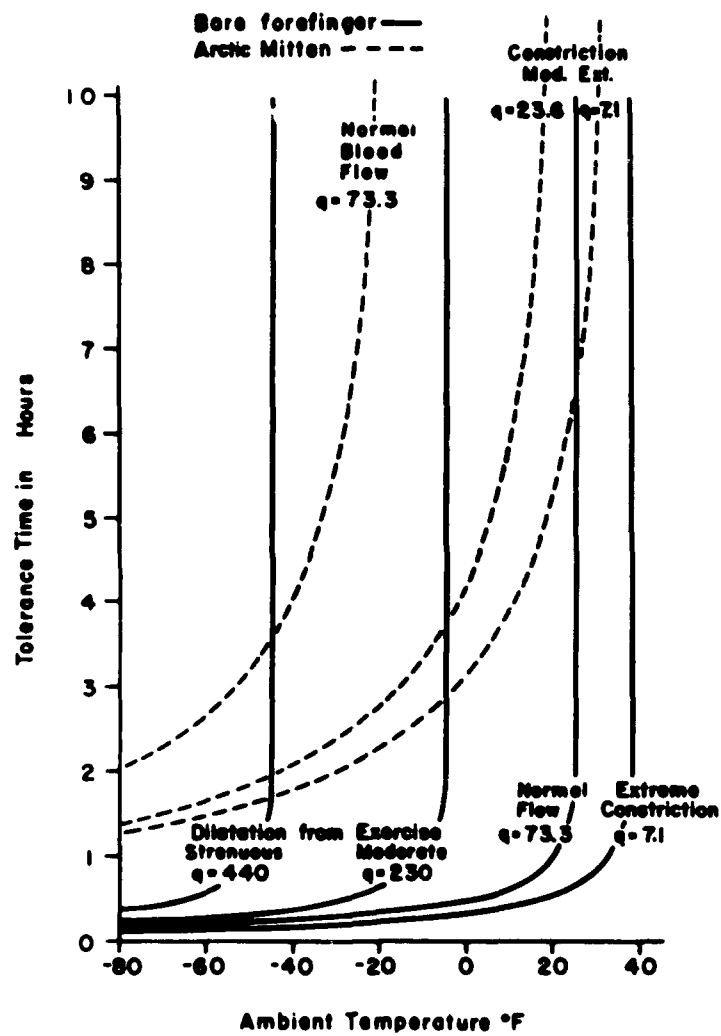
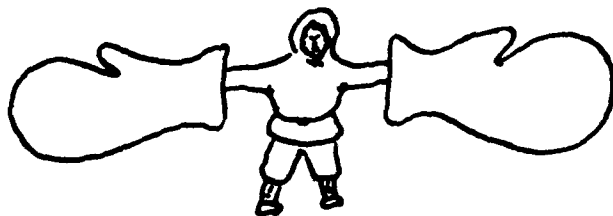
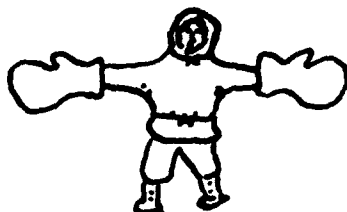


FIGURE 1

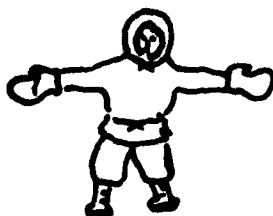
Tolerance time predicted as the time to cool to a finger temperature of 40° F, showing effects of activity level, body heat content and protective mittens.



ANY EXPOSURE, AT REST



6 HOUR EXPOSURE, AT REST



BEST POSSIBLE MITTEN, GOOD FOR  
2-3 HOURS, AT REST



STRENUOUS EXERCISE, NO MITTEN NEEDED

FIGURE 2

Relative size of mitten needed for different exposure times at  
-20° F.

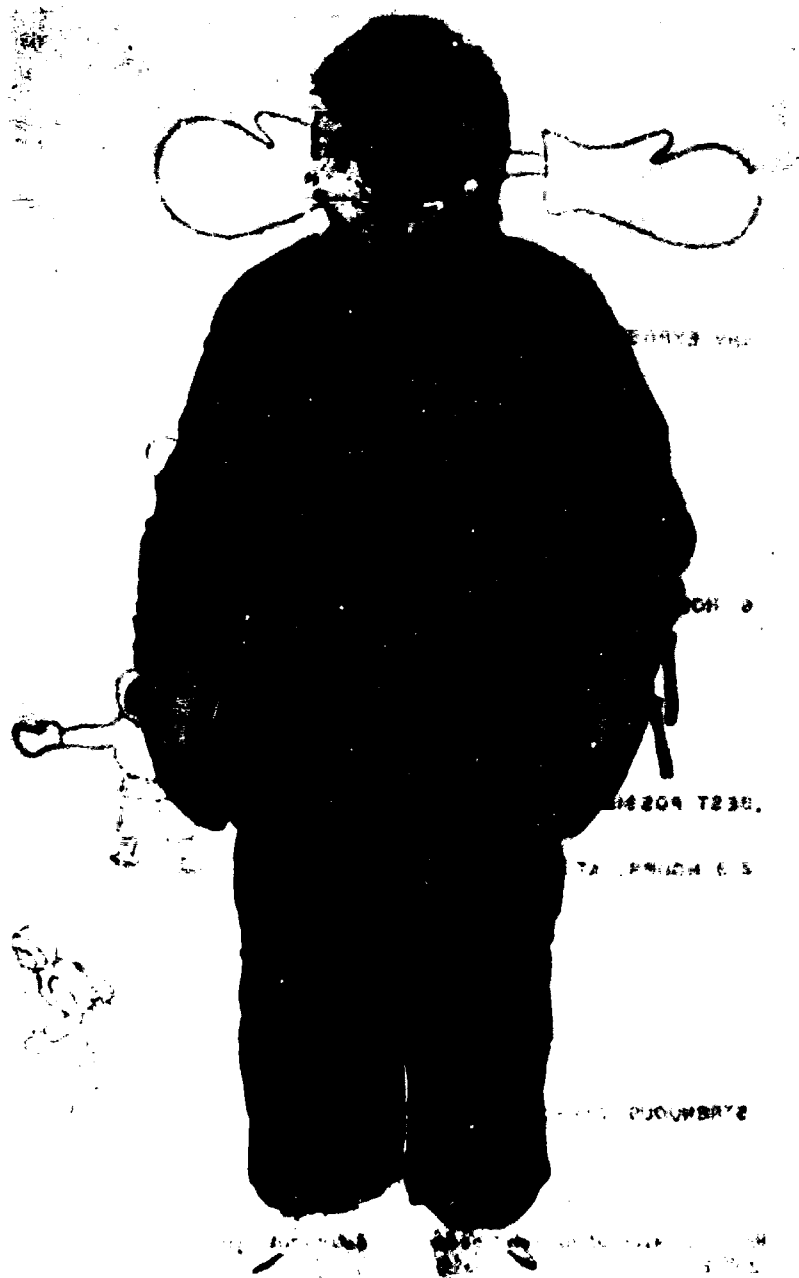


FIGURE 3

The current U. S. Army standard cold-dry  
clothing ensemble.

research program was conducted over a 1-year period in five arctic chamber study phases; the first four at  $-40^{\circ}$  F with a 10 mph wind and the fifth at  $-65^{\circ}$  F also with a 10 mph wind. Three to five different subjects were studied in each phase. The subjects spent the majority of the chamber exposure periods (up to 7 hours on a single day) seated, peering through the arctic hood watching television or movies; standing in groups while talking and while eating a light lunch was allowed, but any exertion was prohibited. Rectal ( $T_R$ ) and mean weighted skin temperature (MWST as the average of 10 points) were continuously measured, using thermocouple probes. Body heat storage ( $\Delta S$ ) was calculated as:

$$\Delta S = 0.83 \times \text{Nude Weight (kg)} \times \frac{(\Delta T_S + 2\Delta T_R)}{3}$$

In phase 1 auxiliary heat was supplied as a fixed flow of heated air delivered to the torso and/or hands and feet via several distribution garments, worn as an extra clothing layer over the long underwear (9); in phases 2 to 5 auxiliary heat was provided as electrical power to gloves and socks knit of wool and insulated resistance wire, worn in place of the standard wool glove and sock. Heat quantities supplied were calculated for the hot air systems by measuring the air flow rate (Brooks rotameter) and the garment inlet air temperature, for the electrical items from their resistance values (Wheatstone bridge) and the voltage output (Weston 0-30 AC voltmeter) of the individual variable transformers (Variac). The Variacs were supplied from a 24-volt transformer, thus limiting voltage and providing electrical isolation. Thermostating of electrically heated items (phases 3 and 4) was accomplished manually, using a thermocouple sited to act as a thermostat-sensing element. Finger cooling from thermostatically controlled set points (phase 4) was studied at hourly intervals (following the second hour of exposure) by shutting off power, removing the outer arctic mitten (a light leather glove was worn between the heating glove and the arctic mitten in this phase) and holding the hands with fingers extended above a chicken wire mesh platform until the fifth finger tip reached  $40^{\circ}$  F, when the outer mittens were replaced and power provided to rewarm the fingers to the selected set point. Phase 5, at  $-65^{\circ}$  F, 10 mph wind, was conducted to validate the system recommended as a result of the first four studies.

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per square meter kilogram calorie per hour. (Blakiston's New Gould Medical Dictionary, First Edition, New York, McGraw-Hill Book Company, Inc., 1949.)

## RESULTS

The results of these studies will be presented in terms of typical individual responses, since there was day-to-day variation in heat supplied and in drape and back pressures of distribution garments.

Hot air supplied continuously to the torso in sufficient quantity to maintain body heat content at pre-exposure control levels ( $\Delta S \approx 0$ ) was inadequate to maintain the integrity of the circulation to the hands and feet, and in all cases the exposure had to be terminated within 2 hours, when finger or toe temperatures reached  $40^{\circ}\text{F}$ , the established lower limit for safety in test procedures at this laboratory. A typical result is shown in Figure 4A; 8.6 cfm of heated air, entering the torso distribution garment at  $110^{\circ}\text{F}$ , provided an available mean enthalpy (calculated with reference to the mean skin temperature at 5-minute intervals during the period when air was being provided) of 0.87 kcal/min. This distribution garment allowed a little heat flow over the hands as well as the torso. Rectal temperature remained essentially constant, and mean weighted skin temperature (MWST) increased slightly during the exposure. Body heat storage rate was only 3 kcal/hr, however, under these environmental conditions equivalent to the subject wearing an 11 clo uniform. While finger temperature was maintained for the first 30 minutes and subsequently slowly increased, the temperature of the toes, which had no warming air supply, slowly fell to  $40^{\circ}\text{F}$  at 72 minutes, when the exposure had to be terminated.

Following this demonstration that "adequate" auxiliary heat supplied continuously to the torso was inadequate to maintain the extremities, the subjects were allowed to cool; then enough heat was supplied to the torso to produce not only repayment of the initial heat lost but a pronounced rise of skin temperature, and even a slight rise of rectal temperature above control values. In spite of a significant accumulated heat load, fingers and toes usually did not share in the rewarming. While finger and toe temperatures decreased much more slowly or plateaued when this "excess" heat was being supplied, in four out of six cases the exposures had to be terminated because of extreme malaise and nausea of the subjects. A typical example is presented (Figure 4B), where after initially cooling for 33 minutes at a rate which was appropriate for the 4.3 clo uniform worn (calculated effective clo: 4), the subject was provided with heat to the torso equivalent

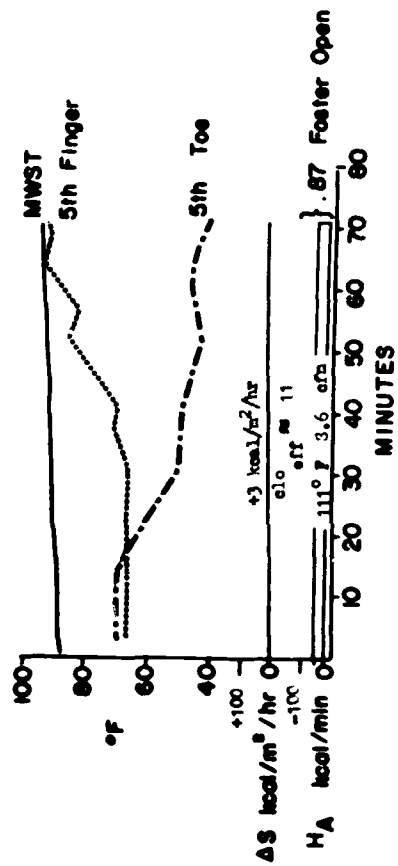


FIGURE 4A

Typical responses to auxiliary heating by hot air supplied primarily to the torso with a small amount to the hands.



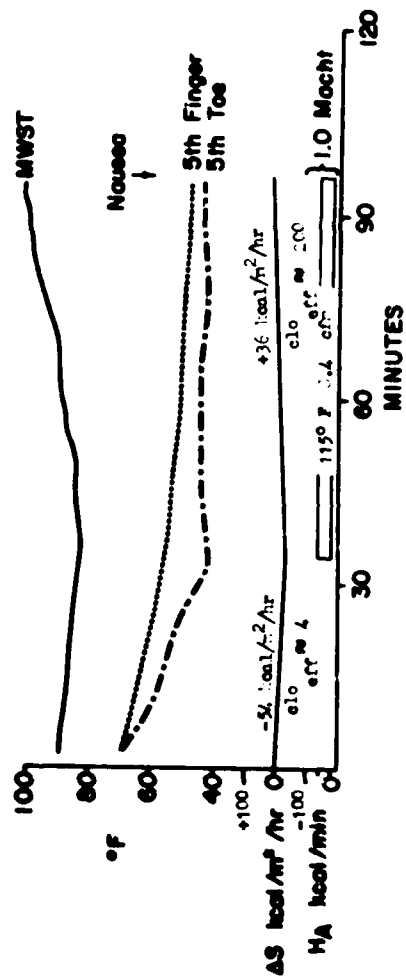


FIGURE 4B

Typical responses to auxiliary heating by hot air supplied in excessive amount to the torso.

to 1 kcal/min. While in general the subject rewarmed as if he were provided with 200 clo of insulation, finger temperature continued to cool, although much more slowly than without the heat to the torso, and toe temperature rose very slightly and then plateaued. After 63 minutes of rewarming of the torso, the subject became dizzy and nauseous, and the exposure had to be terminated.

Taking note of the observation that when rewarming of the fingers did occur (as in Figure 4A), it was associated with the supply of some heated air directly over the surface of the extremity, arrangements were made to supply heated air primarily directly to the hands and feet. Figure 4C demonstrates that with this approach, it was possible to not only maintain the extremity temperatures but also rapidly rewarm extremities that had been allowed to cool. However it was usually difficult, because of differing back pressures, to ensure distribution of heated air to all four extremities, and it appeared that most of the heat supplied was escaping to the ambient environment when the gloves and boots were worn loosely fitted, in order to produce a low pressure drop and thus allow flow of the heated air to the extremity surface.

Accordingly, a second study was initiated to determine the minimum power required to provide heat for the extremities alone, by electrical means. The relationship was sought between power supplied continuously to electrically heated gloves and socks and the extremity temperature maintained. A total of 10 successful man-days of study in which temperatures were maintained at levels above 40° F for 6 hours, and 4 man-days at which power to the hands was inadequate to prevent cooling below 40° F within 2 hours, are represented in Figure 5. It appeared that extremity temperature could be maintained at any desired level between 50 and 105° F, as a function of the power supplied. Above 12 watts of power, which produced a skin temperature of about 85° F, the relationship is linear, a 1° F increase in extremity temperature resulting from each additional watt. Below 12 watts of power the relationship is nonlinear. A minimum of 3 watts per hand or 7 watts per foot is necessary to maintain these extremities above a 40° F temperature. Supply of power levels below these minimums did not appear to extend tolerance times appreciably beyond those experienced without any auxiliary heat. Thus, provision of a total of 20 watts (3 per hand and 7 per foot) appeared to provide adequate protection for continuous exposure at -40° F,

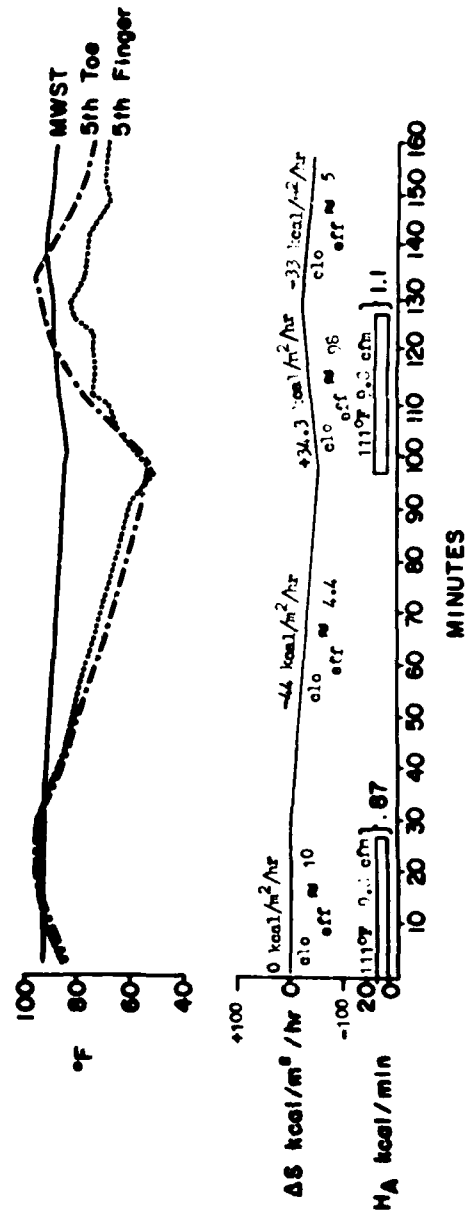


FIGURE 4C

Typical responses to auxiliary heating by hot air supplied only to the hands and feet.

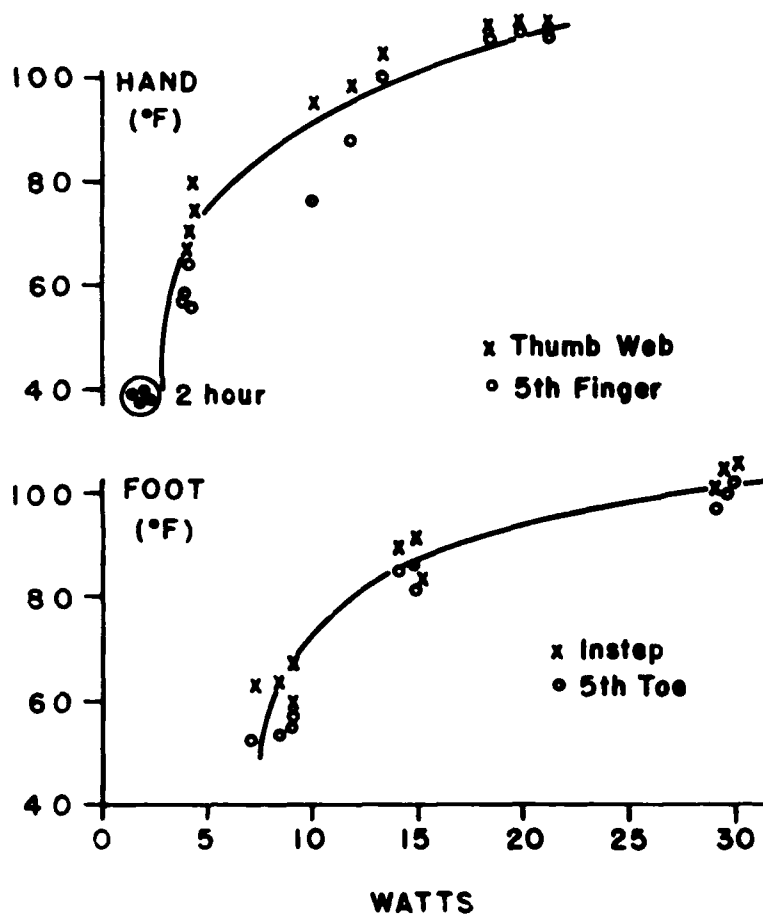


FIGURE 5

The hand and foot temperatures maintained as a function of the power used for auxiliary heated gloves and socks.

10 mph wind. While rectal temperatures fell slightly during the period, the exposures were terminated after 6 hours solely for the convenience of the operating schedule.

Since an active soldier maintains extremity temperatures, and in fact may use the large possible variation in heat input to the extremities as a means of regulating body temperature (15), a third phase was initiated in which thermostating of the extremities was studied. Anatomic consideration suggested that the web between the base of the thumb and the first finger be used as the thermostat site for the hand, but if the footwear were to be thermostated, the most feasible approach was to heat insulated boots rather than the socks. A heated outer glove, rather than the heated liner, was also studied. The results indicated that heating by means of an outer glove doubled the power requirement for the hands, and it was exceedingly difficult to control hand skin temperature from a thermostat sited in the outer glove. On the contrary, very little additional power was required to maintain foot temperatures when the heating element was located in the insulated boot, and thermostating could readily and comfortably be achieved from a site under the fifth toe area in the boot insole. Therefore, it was concluded that the auxiliary heated system should consist of a heated contact glove and a heated insulated boot.

Analysis of the extremity temperatures when the fifth finger was maintained at 60° F identified 68° F as the corresponding temperature for the selected hand thermostat site. However, initial results with this relationship indicated that because of different cooling rates, the fifth finger cooled to 40° F before the thumb web cooled to 68° F. This was corrected by selecting 72° F as the set point temperature; while initially cooling well below the selected 60° F desired maintenance temperature, the fifth finger did not cool below 40° F prior to the initial turn-on of auxiliary heat. No such problem occurred with the feet.

Unfortunately, results indicated that while 3 watts per hand and 7 watts per foot would maintain these extremities, this level of heat was inadequate to produce rewarming to 60° F from the lower initial temperatures occurring before the system came into equilibrium. The power supplied to the thermostated gloves and boots had to be increased to 10 watts each. While this requirement was disappointing, analysis of power demand cycles of four subjects ("on time") revealed that the total power consumption averaged about 20 watt-hours per hand and 40 watt-hours per foot for a 7-hour exposure, or about the same total power consumption

as that required for maintenance of equivalent extremity temperatures with continuous heat. Thus, a power source capable of providing 40 watts was required, but the duty cycle, when the extremities cooled to levels requiring auxiliary heat, would only be about 50% at this power level.

Under the impetus of having to provide a 10-watt-per-hand power level, which would allow an 80° F level of hand temperature to be maintained, in a fourth phase of these studies the additional "tolerance time" (defined as the time to cool any hand point temperature to 40° F) was investigated when the maintained temperature was 80° F rather than 60° F. At every hour of exposure after the second, the four subjects removed the outer arctic mitten. At the same time, auxiliary heat was turned off and cooling to the 40° F level timed. The results in Table I reveal that only 3 or 4 extra minutes were achieved by the considerably greater power consumption required to maintain an 80° rather than 60° F temperature.

The final phase involved a validation of the hardware developed as a result of the first four phases and a study of the capabilities of the system in an extreme environment (-65° F, 10 mph wind). Working in collaboration with clothing and equipment developers of the Army Quartermaster Research and Engineering Center, a snap-acting thermostat was selected, and a 12-volt battery system composed of 11 silver cadmium, 10 ampere, rechargeable cells was fabricated into a canvas vest. The complete system is shown in Figure 6. Since no auxiliary heat is required initially for between 1 to 2 hours, this 120 watt-hour system was designed to provide between 7 and 8 hours of protection for an inactive man at -40° F, 10 mph winds; i. e., 1 to 2 hours of no heat requirement followed by a 50% "on time" demand on four 10-watt heaters for 6 hours. At -65° F, 10 mph wind, five inactive subjects were maintained safely and relatively comfortably for approximately 5 hours, before the drain on the battery power resulted in lowered output voltages and required termination of the exposure.

## DISCUSSION

The difficulties of supplying external heat to the body were studied by Elding, who concluded that for available large areas of the surface, the amount of heat that can be introduced safely

TABLE I

MINUTES TO COOL FROM A MAINTAINED FIFTH FINGER  
TEMPERATURE OF 80° F OR 60° F, AFTER POWER WAS  
SHUT OFF TO A 40° F LEVEL, WITH AND WITHOUT A  
LEATHER GLOVE WINDPROOF SHELL OVER THE  
AUXILIARY HEATING GLOVE.

80 to 40° F		60 to 40° F	
With Shell	Without Shell	With Shell	Without Shell
10	8	8	4
11	6	6	2
20*	4	7	3
11	6	7	6
12	6	8	4
11	7	6	4
6	9	8	6
11	9	11	4
11	7	8	3
11	8	8	3
11	7	8	2
6	8	4	7
8	4	3	6
8	3	4	3
7	4	6	4
6	3	3	4
7	2	4	4
8	-**	4	5
8	-	3	4
10	-	3	4
8	-	3	5
Mean 9.6 min	Mean 6.9 min	Mean 5.9 min.	Mean 4.1 min.

Results represent 21 trials on 4 subjects.

\* Spontaneous rewarming cycle (Lewis wave) interrupted cooling.

\*\* Blank values represent fifth finger temperature initially below  
set points.

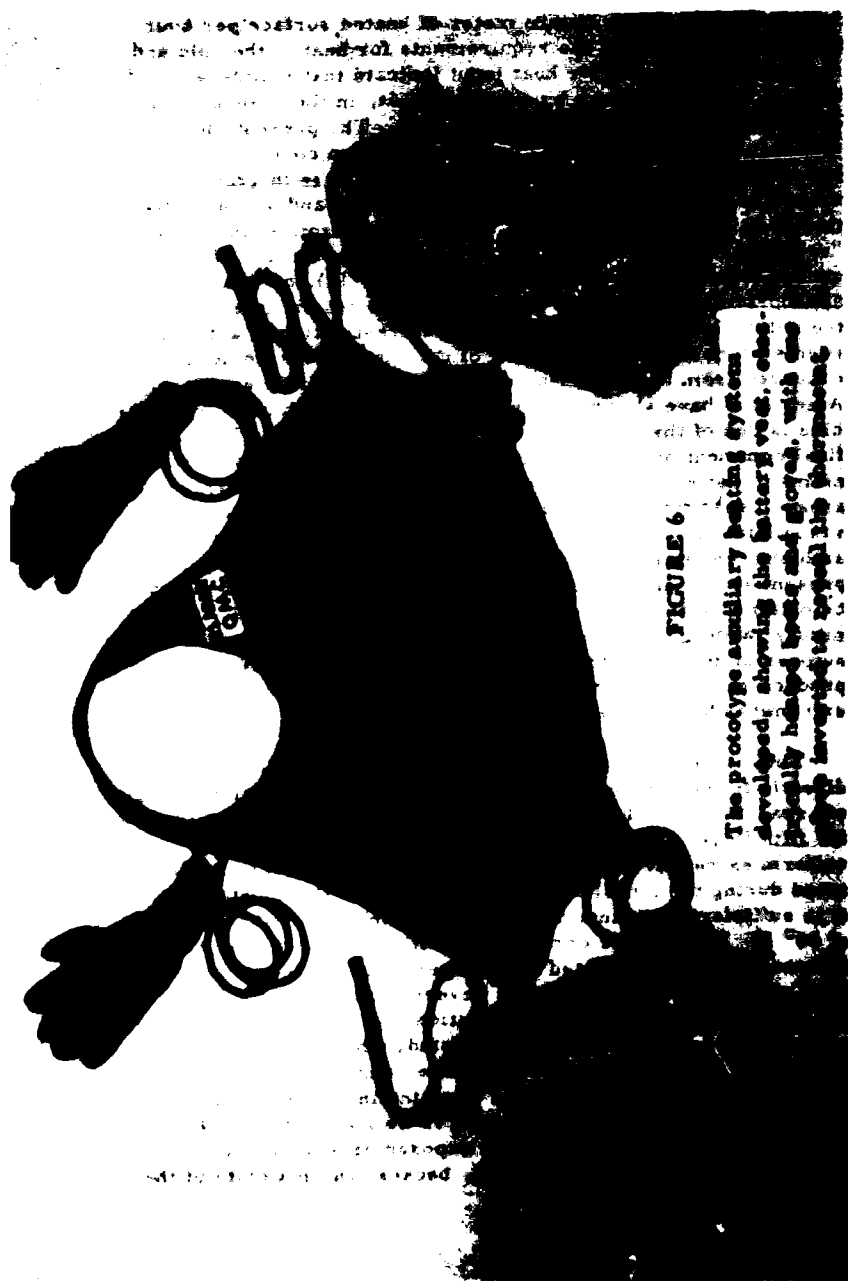


FIGURE 6

The prototype auxiliary heating system developed, showing the battery vent, electrically heated hoses and gloves, with one glove inserted to verify the independent



is about 140 kcal per square meter of heated surface per hour. Calculations based on the requirements for heat in the cold and the surface available for heat input indicate that maintenance of overall thermal balance by auxiliary heat, in the absence of adequate insulation, is an impossibility (2). The present inability to maintain extremity temperatures, or rewarm cooled extremities, by heating the torso even in excessive amount is in general agreement with this work. The subjective malaise and nausea noted in this study with prolonged excessive heat is reminiscent of the "vasovagal syncope" occasionally seen during studies of finger cooling conducted in comfortable ambients (11), but may be more appropriately related to the location of the hot air inlet just above the solar plexus. Without the imposed restriction of activity, it seems probable that rewarming of the extremities would have occurred from this overheated state with very little exercise, as Ames et al have shown that the internal heat production by exercise is one of the most efficient means of rewarming (1). As a final comment on torso heating, a number of studies on mechanisms of indirect warming have led to the concept of "trigger areas," specific body sites where application of heat resulted in vasodilatation of the extremities (5, 7, 12). However, the ambient conditions did not approach the severity of those in the present study, and while an apparently consistent response could be obtained with warmer subjects who were presumably at most mildly vasoconstricted (12), other studies involving heating of a number of suggested trigger areas have failed to consistently produce rewarming when a more severe vasoconstriction of the extremity blood vessels existed (10).

Thus, it appears most practical to supply auxiliary heat directly to the extremity surface. While different thermal lagging of areas of the hand with differing mass to surface-areas (such as the fifth finger and the thumb web) makes maintenance of a uniform extremity temperature difficult and produces problems as noted during the initial cooling with the 68° F thermostat settings, it is sufficient to maintain the "weakest link," the fifth finger tip, at 60° F. This choice corresponds with the lowest hand skin temperature for unaffected manual performance in the cold; it has been shown that performance is severely hindered at a fifth finger tip temperature of 55° F (4). Additionally, very little extra tolerance time was found in the present study when 80° rather than 60° F was selected. While more power capacity is required to rewarm a cooled extremity than to maintain a given temperature with continuous heat, thermostating is well worthwhile. First, because when the man is initially exposed or when he is exercising, no power is required; second, because the majority of the

excess heat required to produce rewarming is apparently stored in the hand and/or the proximal insulation, so that the total watt-hour demand is approximately the same with or without thermostating, the equality being regulated through the relative lengths of the duty cycle.

Biophysical calculations on the relationship between the auxiliary heat supplied electrically and the increase in heat content of the hand (specific heat of tissue  $\times$  mass  $\times \Delta$  temperatures), in the face of such an extreme skin-to-air temperature gradient with only a 2.4 clo insulating arctic mitten assembly, indicate that the electrically supplied heat is grossly insufficient to account for the increased hand temperatures. The slight, continuing decrease in rectal temperatures noted during experiments when auxiliary heating of the extremities was utilized further suggests that under the influence of a warmer extremity microclimate produced by the auxiliary heat, the blood flow from the body core is not as severely limited, and thus heat from the core accounts for the temperature levels maintained during auxiliary heating, particularly over the 55 to 85° F extremity skin temperature range. The shape of the power-temperature maintained relationship (Figure 5), when compared with the data of reference (8) as presented by Molnar (13) for both blood flow through the hand as a function of air temperature and especially hand skin surface temperature as a function of air temperature, further suggests that at the low levels of auxiliary heat being supplied, it is primarily the alteration in blood circulation to the extremities, occurring under the influence of the warmer microclimate produced by auxiliary heating, that accounts for the temperature levels maintained.

Protection for the inactive soldier in extremely cold environments has now been resolved in terms of the parameters of weight and cost. The 7-lb prototype system is adequate to meet the current required military characteristics of providing 8 hours of protection for the inactive man at -40° F with a 3 mph wind. More severe conditions can be met merely by addition of greater watt-hour capacity batteries, at least for conditions up to -65° F with a 10 mph wind; i. e., a windchill of 2400. Since over 90% of the weight of this system is batteries, improvement in the weight factor can be anticipated as power source development improves over the current 16 watt-hours per lb. Reconsideration of the need for some of the current clothing items if auxiliary heat is added also seems practical; e. g., the parka and liner, which weigh 5-1/2 pounds, may prove unnecessary. As torso insulation they may not be necessary per se, and if their role has been

to maintain a warm enough body core so that during even mild activity blood flow to the hands and feet is increased to aid in the dissipation of the extra metabolic heat production, then the parka and liner can well be replaced with the far more effective auxiliary heat. This approach would also aid the overheating during exercise and the resultant production of extra sweat, which collects in the uniform and remains to evaporate after the end of the work period, producing the familiar "after exercise chill." The cost problem would be resolved by quantity procurement.

An even more important immediate use of auxiliary heated handwear and footwear is in areas where power is available. All vehicles, most radio and radar equipment and many missiles all have available power. The auxiliary heating system developed is compatible with a 12- or 24-volt AC or DC power source. Over 90% of the weight and cost of the present system, the battery supply, would be eliminated. Thus, a simple, low cost solution is available for such problems as providing manual dexterity, allowing use of vehicles without heated cabins (such as the mechanical mule) and permitting reasonably long periods of light work in restricted but underheated or unheated areas. This solution has not as yet been exploited.

This solution is also useful in the area of extending research. Almost all tests of cold weather clothing have been terminated because of cold extremities, and identification of improved torso clothing has been confounded by these related, but not totally dependent, appendages to the torso. There is also a hierarchy of the weak links in protection in the cold; after the hands and feet comes the face, but face protection has been unresolved, in part because of the dominance of the problems of protecting the extremities. From the present studies, we have already identified the next weak link with the current cold-dry uniform — the lower legs and arms. Previously overlooked, perhaps unrecognized as a result of the dominance of the extremity problem, is the fact that the insulation provided the lower arms and legs is less effective than that provided the rest of the body. This weakness may be contributing to the problem of protecting the extremities. Finally, in terms of the long-range goal of a comfortable, adjustable microclimate for the soldier or space man, produced without excessive weight by a synthesis of advanced clothing, physiological, mechanical and electrical knowledge, auxiliary heating of the extremities seems to be an encouraging step in the right direction.

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